W Boson Polarization in Top Quark Decay at CDF

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What Could We Learn?

Testing the weak decay of the top quark

- Expected to be described by the charged-current weak interaction of the Standard Model
  - ▷ Believed to be purely vector-minus-axial-vector $(V - A)$
- Higgs mechanism gives rise to the longitudinal polarization state of the W
- Standard Model gives specific predictions for fractions of longitudinal and transverse W bosons in top decay

$$BR(t \to W_{\lambda=0} b) = \frac{m_t^2}{m_t^2 + 2m_W^2} \sim 70\% \qquad BR(t \to W_{\lambda=-1} b) = \frac{2m_W^2}{m_t^2 + 2m_W^2} \sim 30\%$$

Could reveal new physics

- Verify that we have indeed observed the SM top quark
- Test for $V + A$ structure in the charged-current weak interaction
- Longitudinal W is intimately related to EWSB in the SM
  - ▷ Top quark decay is the only significant source of longitudinal W bosons

What do you mean by "W polarization"?

Helicity is the projection of spin along the direction of motion

- This is defined by the helicity operator: $\vec{\sigma} \cdot \hat{p}$
- Helicity value for the W polarization states are then -1 and $+1$ for $\vec{\epsilon}_L$ and $\vec{\epsilon}_R$, respectively
  - ▷ Transverse W
- Assume that the direction of motion is $\hat{z}$, then a W with a polarization of $\vec{\epsilon}_z$ has helicity 0
  - ▷ Longitudinal W

Squares of the various helicity amplitudes

- These are well-known:

$$|\mathcal{M}(W^+_{\lambda=-1})|^2 = |\mathcal{M}(W^-_{\lambda=+1})|^2 = \frac{1}{4}(1 - \cos\theta^*)^2$$

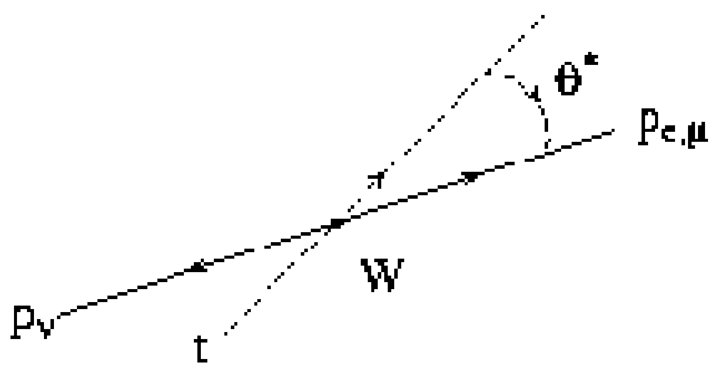
$$|\mathcal{M}(W^+_{\lambda=+1})|^2 = |\mathcal{M}(W^-_{\lambda=-1})|^2 = \frac{1}{4}(1 + \cos\theta^*)^2$$

$$|\mathcal{M}(W^+_{\lambda=0})|^2 = |\mathcal{M}(W^-_{\lambda=0})|^2 = \frac{1}{2}(\sin\theta^*)^2$$

Techniques for measuring W polarization

The angle θ^*

- Defined as the angle between charged-lepton momentum in W rest-frame and the W momentum in the top rest-frame (image)
- We can use the dilepton sample
  - ▷ $t\bar{t}$ events where both W bosons decay to e and/or μ
- We can also use the lepton+jets sample
  - ▷ $t\bar{t}$ events where only one W decays to e or μ
- Extremely difficult to use the all-hadronic sample for this analysis
  - ▷ We need the charges of the daughter quarks!



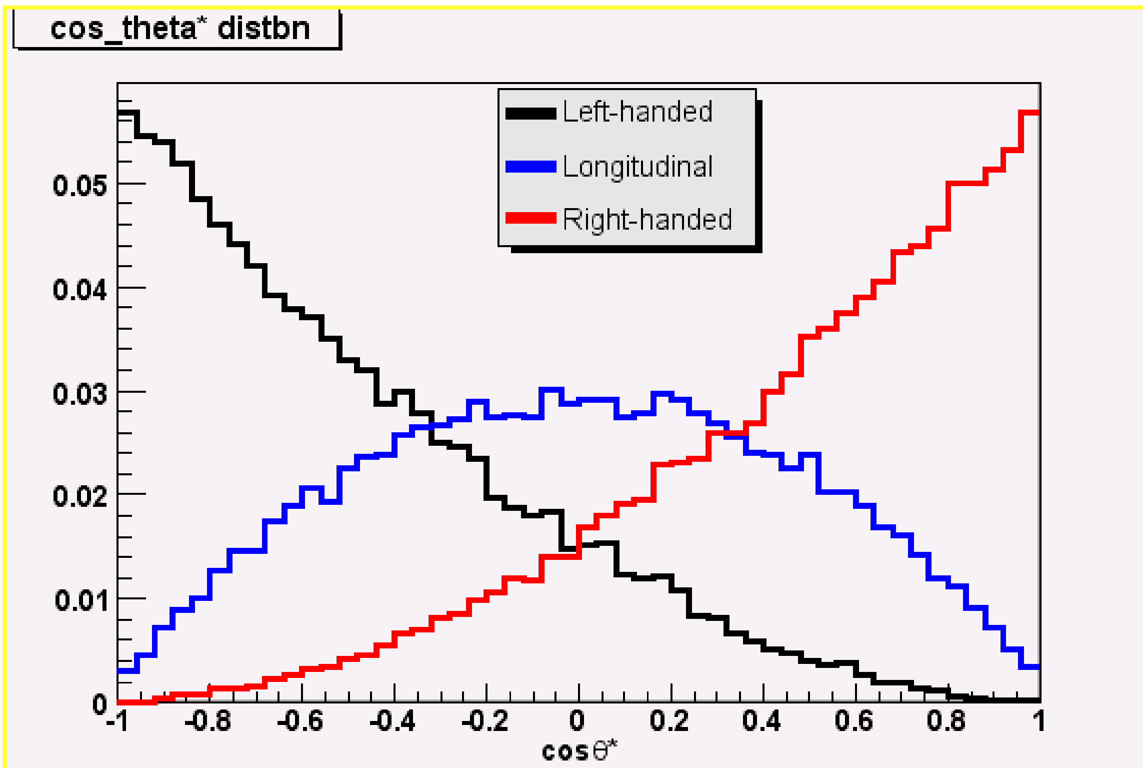
At least two methods

Measure the angle $\cos\theta^*$ directly by reconstruction

- We make use of the relation:

$$\cos\theta^* = \frac{2m_{lb}^2}{m_t^2 - M_W^2} - 1$$

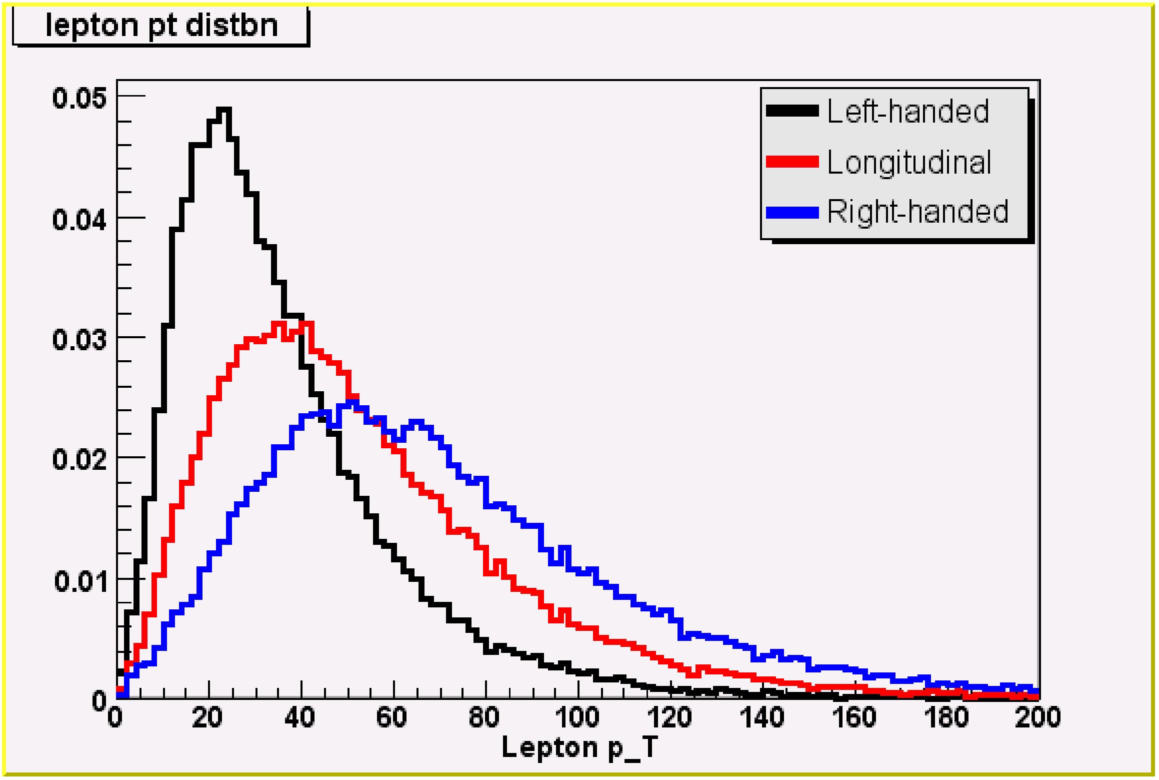
▷ m_{lb} is the invariant mass of the lepton and the b



Alternatively...

Measure the lepton p_T in the lab frame

- This is the most precisely measured quantity in a non-hadronic top event
- In longitudinal ($\lambda_W = 0$) W decay, charged lepton most likely to travel perpendicular to the W momentum (as viewed from the top rest frame)
- In transverse ($\lambda_W = -1$) W decay, charged lepton most likely to travel opposite the W momentum (as viewed from the top rest frame)



How well can we measure W polarization?

Previous measurement

- Fraction of longitudinal Ws in top decay measured during Run I at CDF
  - ▷ Using the lepton-p_T method
  - ▷ CDF Collaboration, T. Affolder et al., Phys. Rev. Lett. 84 216 (2000).

$$F_{\lambda_W=0} = 0.91 \pm 0.37(stat) \pm 0.13(syst)$$

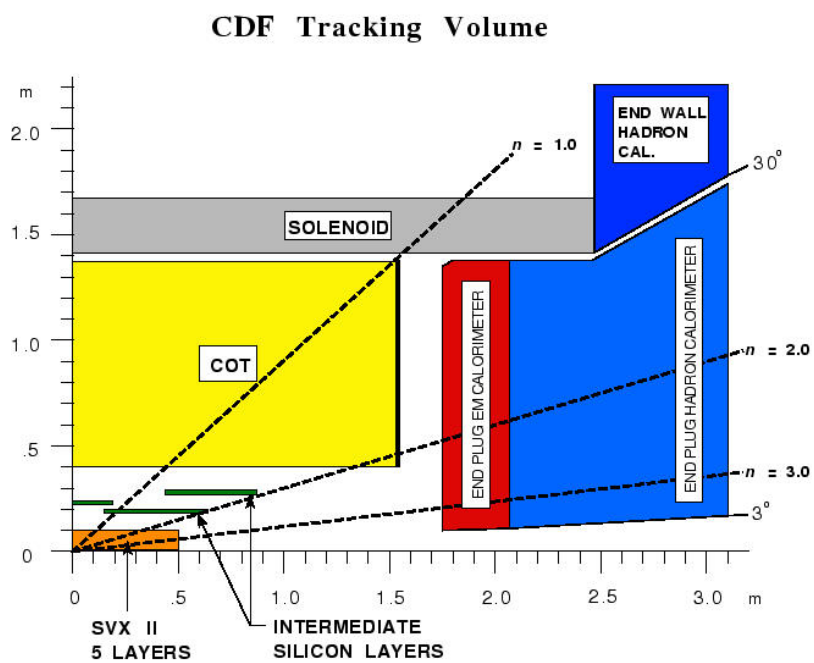
How well can we do during Run II at CDF?

- Increased $\int \mathcal{L} dt$
- Increased $t\bar{t}$ cross-section (due to higher CM energy)
  - ▷ More top quarks, lower statistical error
  - ▷ Better handle on backgrounds and systematics
- Improved tracking, higher b-tagging efficiency
  - ▷ Lower systematic errors
- Sensitivity at CDF during Run II is the subject of this talk

The Run II Collider Detector at Fermilab (CDF)

A general purpose solenoidal detector at FNAL...

- Silicon Vertex Detector (SVX)
  - ▷ Double-sided to provide $r - z$ readout
  - ▷ Three-dimensional vertex reconstruction
  - ▷ Excellent for secondary vertex detection close to the interaction point (IP)
  - ▷ Ideal for b-quark ''tagging''



The Run II Collider Detector at Fermilab (CDF)

...Actively taking data

- Central Outer Tracker (COT)
  - ▷ Charged particle tracking in the region $|\eta| \leq 1.0$
  - ▷ Open-cell drift chamber contained within volume of the solenoid
  - ▷ p_T resolution of $\delta p_T / p_T^2 \simeq 0.3\%$ (GeV/c)$^{-1}$
- Calorimetry
  - ▷ Measures EM and HAD energy deposition in the region $|\eta| \leq 3.0$
  - ▷ Average resolution EM $\sim 20\%/\sqrt{E_T}$
  - ▷ Average resolution HAD $\sim 60\%/\sqrt{E_T}$
- Muon Detectors
  - ▷ Muon detection through four layers of single-wire drift cells
  - ▷ Furthest detectors from the IP
  - ▷ Muon detection in $|\eta| \leq 1.5$ and nearly complete coverage in ϕ
- Data acquisition and storage
  - ▷ Three-tier trigger system
  - ▷ Upon acceptance by all three triggers, event written out for permanent storage
  - ▷ Average event size ~ 250 kB

A generator-level sensitivity study

Generation of signal distributions for each helicity

- Generated 20,000 $t\bar{t}$ events for each helicity value
- Extracted both $\cos\theta^*$ and lepton p_T distributions
- This study was done at the generator level, no detector simulation

Fitting the signal distributions

- Each of the signal distributions were fit with user-defined functions
- This was done for each method and each helicity
- Fitting the distributions creates two sets of signal templates
  - T^-, T^0, and T^+
  - One set for each of the two methods

The likelihood fitter

Used an unbinned maximum likelihood fitter

- Used to perform generator-level sensitivity study
- Fitter has the form:

$$\mathcal{L} = \prod_{i=1}^{N} P_i^{sig}$$

  - ▷ i is the index over input events
  - ▷ P_i^{sig} is the signal probability density function (PDF)

- Two signal PDFs are considered:

$$P^{sig} = (1 - F_0)T^- + F_0 T^0$$

$$P^{sig} = (1 - F_0 - F_{+1})T^- + F_0 T^0 + F_{+1} T^+$$

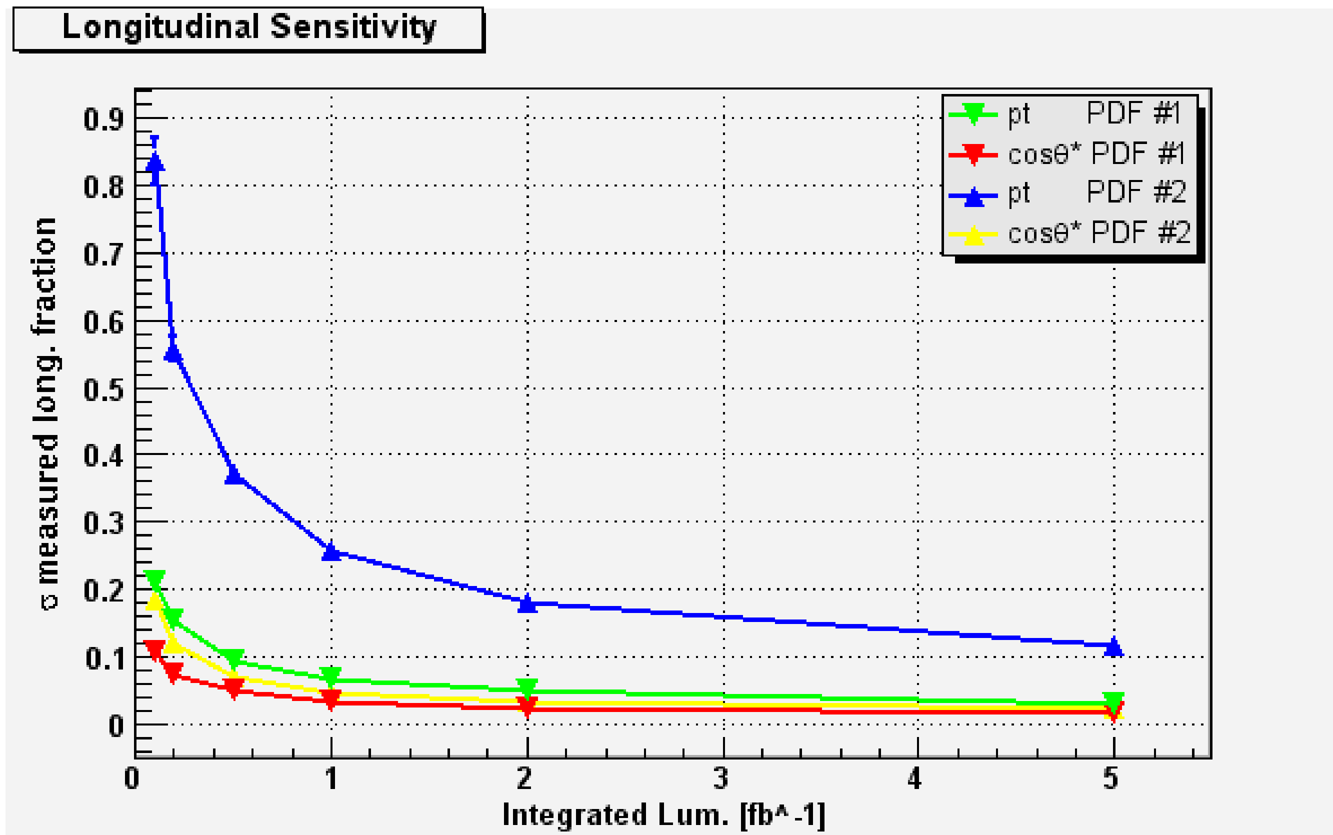
  - ▷ T^-, T^0 and T^+ describe the signal components

- Fitter developed using the RooFit toolkit for data modeling
  - ▷ http://roofit.sourceforge.net

The sensitivity study results

Study carried out using lepton-p_T and $\cos\theta^*$ templates

- 1000 pseudo-experiments for several data sizes
- Fitted values for $F_{\lambda_W=0}$ and $F_{\lambda_W=+1}$ obtained
- Plotted below is the absolute uncertainty on measured $F_{\lambda_W=0}$



The sensitivity study results

Study carried out using lepton-p_T and $\cos\theta^*$ templates

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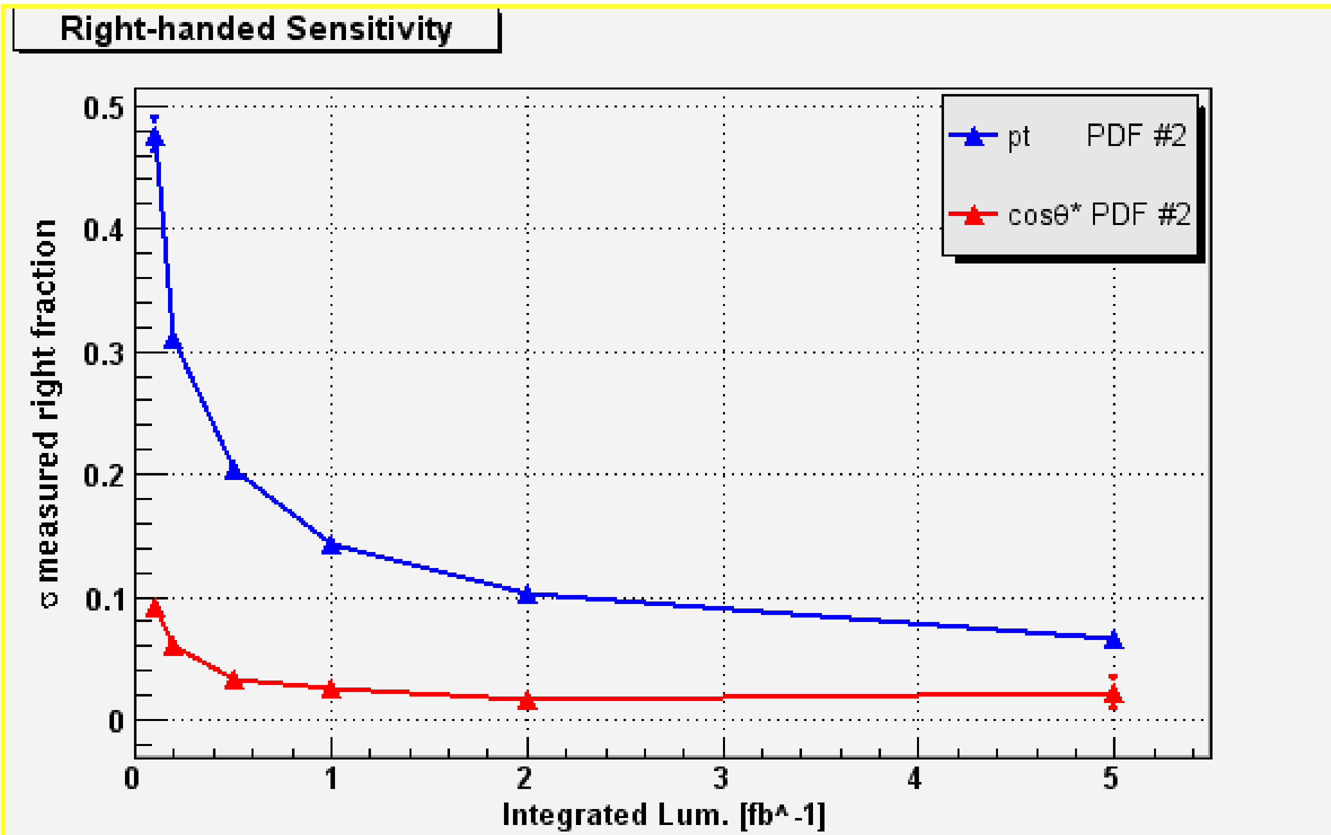
- Plotted below is the absolute uncertainty on measured $F_{\lambda_W=+1}$



Conclusions

Generator-level background-free sensitivity study

- Lepton p_T and $\cos\theta^*$ methods show comparable sensitivity
- With ~2 fb^{-1} of data measurement of transverse and longitudinal fractions to $\pm$ 2% $(stat)$
  - ▷ This study neglected detector effects and backgrounds
- Systematic uncertainties will certainly come into play
  - ▷ From Run I with ~0.1 fb^{-1} this was $\pm$ 13% $(syst)$

More realistic simulations are already underway

- Starting to include backgrounds
- Working on the mass fitter which is needed for $\cos\theta^*$ method

We are starting to look at W polarization in Run II data

- See you next year!